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User's Manual for FEM-BEM Method

Version 1.0

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December 2002

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ABSTRACT

A user's manual for using FORTRAN code to perform electromagnetic scattering analysis of arbitrarily shaped material cylinders using a hybrid method that combines the finite element method (FEM) and the boundary element method (BEM) [1]. In this method, the material cylinder is enclosed by a fictitious boundary and the Maxwell's equations are solved by FEM inside the boundary and by BEM outside the boundary. The electromagnetic scattering on several arbitrarily shaped material cylinders using this FORTRAN code is computed to as examples.

1.0 INTRODUCTION

The hybrid approach depicted in [1] retains the advantages of both differential equation and integral equation approaches. The general procedure for a hybrid technique requires that the scatterer be enclosed by an artificial boundary. Maxwell's equations are then solved by a differential equation approach such as the finite element method (FEM) inside the artificial boundary and by an integral equation approach in discretized form such as the boundary element method (BEM) outside the artificial boundary. Although use of BEM on and outside the artificial boundary results in a full dense matrix, convergence of an approximate solution to the exact solution is guaranteed without a change in the location of the artificial boundary.

FORTRAN code used to perform this hybrid method has been developed and the remainder of this paper depicts the steps in its use including examples. Section 2 contains instructions for installing the code, and Section 3 demonstrates operation of the code. Section 4 contains sample runs as examples for operating the code including step-by-step instructions and the contents of input files. Section 5 contains the results of several additional test cases.

2.0 INSTALLATION OF THE CODE

The FORTRAN code used to perform this hybrid method can be run on any FORTRAN platform. Along with the executable FORTRAN file, the *.MOD file containing the required mesh information, and then Fort.11 file containing the user input must be placed in the same directory. These files will be more thoroughly discussed in Section 3.

3.0 OPERATION OF THE CODE

The computation scattering from a specific geometry with the scattering code is a multi-stage process as illustrated in Diagram 1. The geometry of the problem has to be constructed with the help of any commercial Computer Aided Design (CAD) package. In this case, COSMOS/M was used as the geometry modeler and meshing tool. As the infinite ground plane is accounted for in the formulation of the theory, only the geometry needs to be constructed using the geometry modeler.

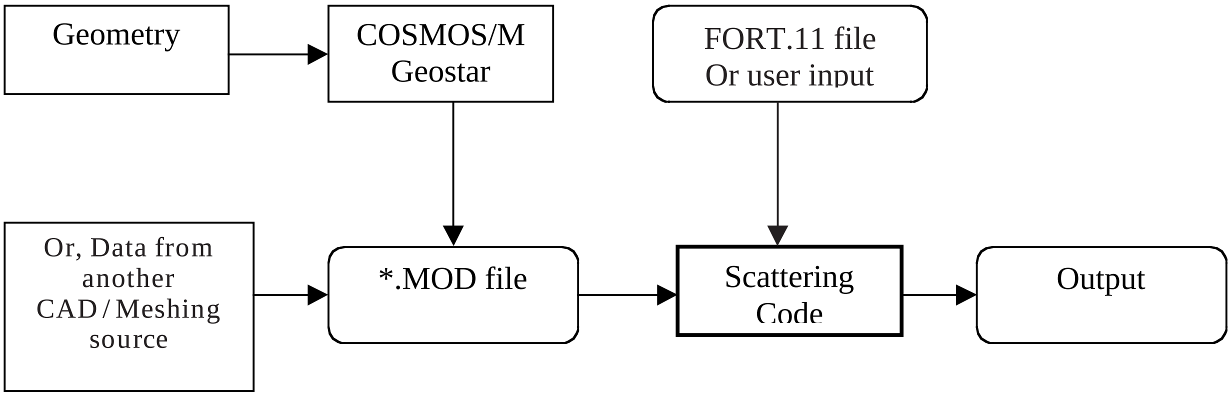

Diagram 1: Flow chart showing steps involved in computing scattering using code

The geometry of the model is constructed and meshed with any commercial Computer Aided Design package such as COSMOS/M. The user is assumed to be familiar with COSMOS/M package and its features. A sample *.SES file of COSMOS/M follows:

```
C*
C*  COSMOS/M      Geostar V2.00
C*  Problem: example1   Date:  5- 8- 2  Time : 14:56:17
C*
PLANE,Z,0,1
VIEW,0,0,1,0
PT,1,0,0,0
PT,2,1,0,0
CRPCIRCLE,1,1,2,1,360,4
CRPCIRCLE,5,1,2,1.2,360,4
SCALE,0
CT,1,.0,.1,4,5,6,7,8,0
CT,2,0,.1,4,1,2,3,4,0
RG,1,2,1,2,0
EGROUP,1,TRIANG,0,0,0,0,0,0,0,0
MPROP,1,PERMIT,1,MPERM,1
MA_RG,1,1,1,3,1,0
NPCT,1,10,1,1
NPCT,2,0,2,1
```

The *.MOD file then can be generated with required mesh information. The code accepts the *.MOD file as input and generates the data.

The scattering code gives the following prompts:

```
Do you want to input parameter data from the
keyboard or read it from an input file?
Type 0 for keyboard, Type 1 for file
```

If the user chooses 0, keyboard input, then the following prompts are given:

```
Enter input file name
```

The input file is the name of the *.MOD file.

```
Enter output file name
```

The output file is named at the discretion of the user.

```
Enter polarization type:
Enter 0 for TM case or 1 for TE case
```

The model can be excited by either a TM-polarized plane wave or a TE-polarized plane wave, the user chooses the case with a 0 for TM or a 1 for TE.

```
Enter frequency of operation in GHz
```

The user enters the frequency at which the model is run in gigahertz. (e.g., 30)

```
Enter incidence angle in degrees
```

The user inputs the angle of incidence at which the model is run in degrees. (e.g., 180)

```
Enter RCS required:
Enter 0 for bistatic or 1 for monostatic
```

The user chooses the type of scattering at which to run the model, choosing 0 for bistatic and 1 for monostatic.

```
Enter number of regions
```

The user inputs the number of regions constructed in the model needing the dielectric constants identified. (NOTE: At this time, only two regions are considered.)

```
Enter dielectric constants of regions
Enter TE dielectric constant for 1 outermost region
```

The user inputs the electric permittivity of the substrate in the first outermost region as a complex number. (e.g., 1,0)

```
Enter TM dielectric constant for 1 outermost region
```

The user inputs the magnetic permittivity of the substrate in the first outermost region as a complex number. (e.g., 1,0)

```
Enter TE dielectric constant for 2 outermost region
```

The user inputs the electric permittivity of the substrate in the second outermost region as a complex number. (e.g., 1,0)

```
Enter TM dielectric constant for 2 outermost region
```

The user inputs the electric permittivity of the substrate in the second outermost region as a complex number. (e.g., 1,0)

If the user chooses 1, file input then file must be named fort.11 and contain the same information as asked for above. The fort.11 file must look as follows:

TEMP4.MOD	the name of the input *.MOD file
TEMP4.OUT	the user chosen name of the output file
0	0 for TM, 1 for TE
30	frequency
180	angle of incidence
0	0 for bistatic, 1 for monostatic
2	# of regions
1.,0.	TM of outermost region
1.,0.	TE of outermost region
1.,0.	TM of second outermost region
1.,0.	TE of second outermost region

The scattering code generates the *.OUT file which contains the number of nodes used, the number of elements used, and the number of fixed potential points. The file also contains a listing of the angles used starting at 1 degree and incrementing by 1 degree through 180 degrees followed by the RCS value at each angle.

4.0 SAMPLE RUNS

Three example runs are illustrated in this section. One is the bistatic scattering width of a conducting cylinder. The second is the bistatic scattering width of a coated conducting circular cylinder. The third is the monostatic scattering width of a conducting strip.

Example 1: Bistatic scattering width of a conducting cylinder

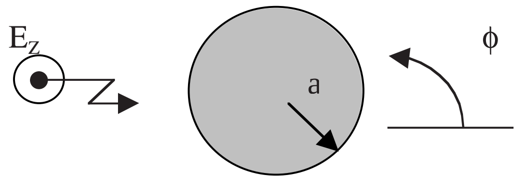

Figure 1: Conducting cylinder

A conducting cylinder with radius of 1.0λ and angle of incidence 180° as shown in Figure 1 is considered. The bistatic scattering was computed in a constant θ-plane at θ = 30° for ϕ = 0° to 180° with E-polarized incidence wave.

*.SES file as follows:

```
C*
C*  COSMOS/M      Geostar V2.00
C* Problem : example1           Date :  5- 8- 2  Time : 14:56:17
C*
PLANE,Z,0,1
VIEW,0,0,1,0
PT,1,0,0,0
PT,2,1,0,0
CRPCIRCLE,1,1,2,1,360,4
CRPCIRCLE,5,1,2,1.2,360,4
SCALE,0
CT,1,.0,.1,4,5,6,7,8,0
CT,2,0,.1,4,1,2,3,4,0
RG,1,2,1,2,0
EGROUP,1,TRIANG,0,0,0,0,0,0,0,0
MPROP,1,PERMIT,1,MPERM,1
MA_RG,1,1,1,3,1,0
NPCT,1,10,1,1
NPCT,2,0,2,1
```

Fort.11 file as follows:

```
TEMP1.MOD
TEMP1.OUT
0
30
180
0
2
1.,0.
1.,0.
1.,0.
1.,0.
```

The following shows the user interface:

```
%a.out
      Do you want to input parameter data from the
      keyboard or read it from an input file?
      Type 0 for keyboard, Type 1 for file
      1
      Number of Nodes = 218
      Number of elements, nelmts1 = 296
      Number of elements, nelemts2 = 0
      Number of boundary nodes = 140
      Number of nodes on outer boundary = 76
      *.MOD file read correctly
      FEM Matrix is complete!
      BOUNDARY NODES ARE IN SEQUENCE
%
```

The following shows a portion of the TEMP1.OUT data:

```
Number of Nodes Used =   405
Number of Elements Used =      682
Number of Fixed Potential Points  =    128
0.E+0,  12.1933088
1.,  12.1849098
2.,  12.1596003
3.,  12.1174145
4.,  12.0583963
5.,  11.9826269
6.,  11.8901615
7.,  11.7811155
8.,  11.6556025
9.,  11.5137615
10.,  11.3557796
11.,  11.181859
12.,  10.9922733
13.,  10.787343
14.,  10.5674543
15.,  10.3331203
.
.
.
```

Example 2: Bistatic scattering width of a coated conducting cylinder A

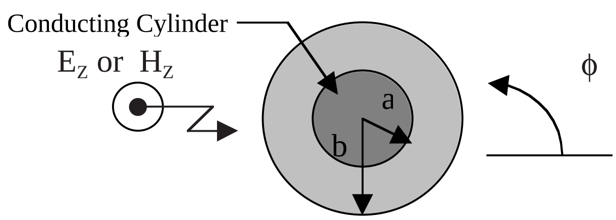

Figure 2: Coated Conducting Cylinder A

A coated conducting cylinder with inner radius of 1.0λ, outer radius of 1.5λ, angle of incidence 180°, and $\varepsilon_r = 2.0$ and $\mu_r = 1.0$ as shown in Figure 2 is considered. The bistatic scattering was computed in a constant θ-plane at θ = 30° for ϕ = 0° to 180° with E-polarized incidence wave.

*.SES file as follows:

```
C*
C*  COSMOS/M      Geostar V2.00
C* Problem : example3           Date :  5- 8- 2  Time : 15:31:51
C*
PLANE,Z,0,1
VIEW,0,0,1,0
PT,1,0,0,0
PT,2,1,0,0
CRPCIRCLE,1,1,2,1,360,4
CRPCIRCLE,5,1,2,1.5,360,4
SCALE,0
CT,1,0,.1,4,5,6,7,8,0
CT,2,0,.1,4,1,2,3,4,0
RG,1,2,1,2,0
EGROUP,1,TRIANG,0,0,0,0,0,0,0,0
MPROP,1,PERMIT,1,MPERM,1
MA_RG,1,1,1,3,1,0
NPCT,1,10,1,1
NPCT,2,0,2,1
```

Fort.11 file as follows:

```
TEMP2.MOD
TEMP2_TM.OUT
0
30
180
0
2
2.,0.
1.,0.
1.,0.
1.,0.
```

The following shows the user interface:

```
%a.out
      Do you want to input parameter data from the
      keyboard or read it from an input file?
      Type 0 for keyboard, Type 1 for file
      1
      Number of Nodes = 489
      Number of elements, nelmts1 = 818
      Number of elements, nelemts2 = 0
      Number of boundary nodes = 160
      Number of nodes on outer boundary = 96
      *.MOD file read correctly
      FEM Matrix is complete!
      BOUNDARY NODES ARE IN SEQUENCE
%
```

The following shows a portion of the TEMP2_TM.OUT data:

```
Number of Nodes Used =   489

Number of Elements Used =      818

Number of Fixed Potential Points  =    160
 0.E+0,  20.6663094
 1.,  20.6083965
 2.,  20.4261665
 3.,  20.1157284
 4.,  19.6702042
 5.,  19.0789776
 6.,  18.3265228
 7.,  17.3903446
 8.,  16.2375145
 9.,  14.8184109
 10.,  13.0548906
 11.,  10.8161774
 12.,  7.86832523
 13.,  3.80035973
 14.,  -1.16311979
 15.,  -0.273486018
 16.,  4.03294611
 17.,  7.06164789
 18.,  9.09325123
 19.,  10.4794235
 20.,  11.4103079
 21.,  11.9899607
 22.,  12.2767601
 23.,  12.3020439
 24.,  12.0785599
 25.,  11.6034975
 26.,  10.8576984
 .
 .
 .
```

Example 3: Monostatic scattering width of a conducting strip

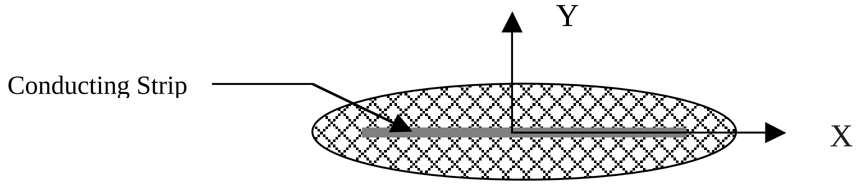

Figure 3: Conducting Strip

A conducting strip (infinite along z) of length 2.2λ, width of 0.04λ, and angle of incidence 180° with an artificial elliptical boundary with major axis 1.3λ and minor axis 0.3λ as shown in Figure 3 is considered. The monostatic scattering was computed in a constant θ-plane at θ = 30° for ϕ = 0° to 180° with E-polarized incidence wave.

*.SES file as follows:

```
C*
C*  COSMOS/M      Geostar V2.00
C* Problem : example10          Date :  5- 9- 2  Time : 12:49:15
C*
PLANE,Z,0,1
VIEW,0,0,1,0
PT,1,0,0,0
PT,2,1.1,.02,0
PT,3,1.1,-.02,0
PT,4,-1.1,-.02,0
PT,5,-1.1,.02,0
SCALE,0
PT,6,1.3,0,0
PT,7,0,.3,0
SCALE,0
CRELLIPSE,1,6,7,1,4
SCALE,0
CRLINE,5,2,3
CRLINE,6,3,4
CRLINE,7,4,5
CRLINE,8,5,2
CT,1,0,.1,4,1,2,3,4,0
CT,2,0,.1,4,5,6,7,8,0
RG,1,2,1,2,0
EGROUP,1,TRIANG,0,0,0,0,0,0,0,0
MPROP,1,PERMIT,1,MPERM,1
MA_RG,1,1,1,3,1,0
NPCT,1,10,1,1
NPCT,2,0,2,1
```

Fort.11 file as follows:

```
TEMP3.MOD
TEMP3_TM.OUT
0
30
180
0
2
1.,0.
1.,0.
1.,0.
1.,0.
```

The following shows the user interface:

```
%a.out
      Do you want to input parameter data from the
      keyboard or read it from an input file?
      Type 0 for keyboard, Type 1 for file
      1
      Number of Nodes = 179
      Number of elements, nelmts1 = 256
      Number of elements, nelemts2 = 0
      Number of boundary nodes = 102
      Number of nodes on outer boundary = 56
      *.MOD file read correctly
      FEM Matrix is complete!
      BOUNDARY NODES ARE IN SEQUENCE
%
```

The following shows a portion of the TEMP3_TM.OUT data:

```
Number of Nodes Used =   179
Number of Elements Used =      256
Number of Fixed Potential Points  =    102
 0.E+0,  8.1462965
 1.,  8.14550304
 2.,  8.1434927
 3.,  8.14020443
 4.,  8.13552952
 5.,  8.1293211
 6.,  8.12139606
 7.,  8.11152649
 8.,  8.09944344
 9.,  8.08484364
 10.,  8.06738091
 11.,  8.04666805
 12.,  8.02227306
 13.,  7.99373865
 14.,  7.96056461
 15.,  7.92220163
 16.,  7.87807846
  .
  .
  .
```

5.0 TEST CASES

Test Case 1: Bistatic scattering width of a conducting cylinder

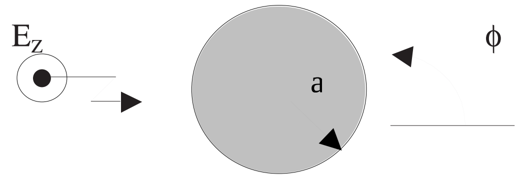

Figure 4: Conducting cylinder

A conducting cylinder with radius of 1.0λ and angle of incidence 180° as shown in Figure 4 is considered. The bistatic scattering was computed in a constant θ-plane at θ = 30° for ϕ = 0° to 180° with E-polarized incidence wave and then an H-polarized incidence wave.

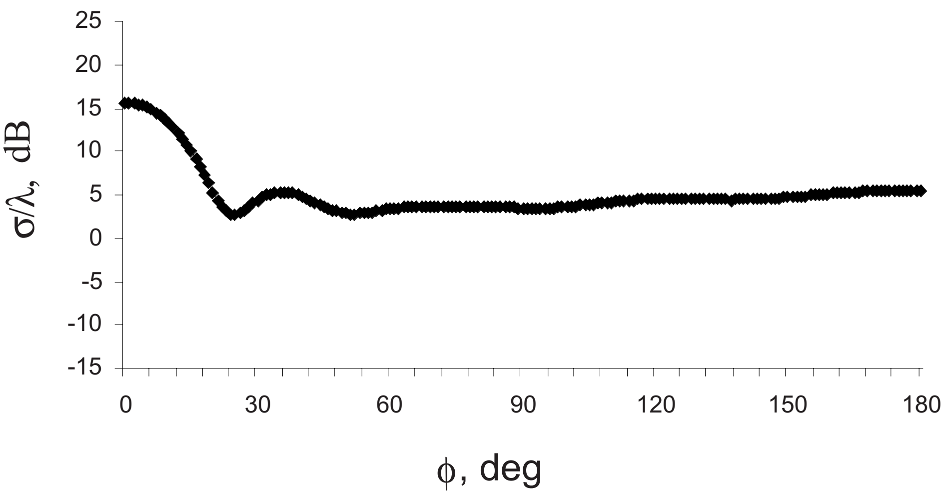

Figure 5: Conducting cylinder graph, E-polarized incidence wave

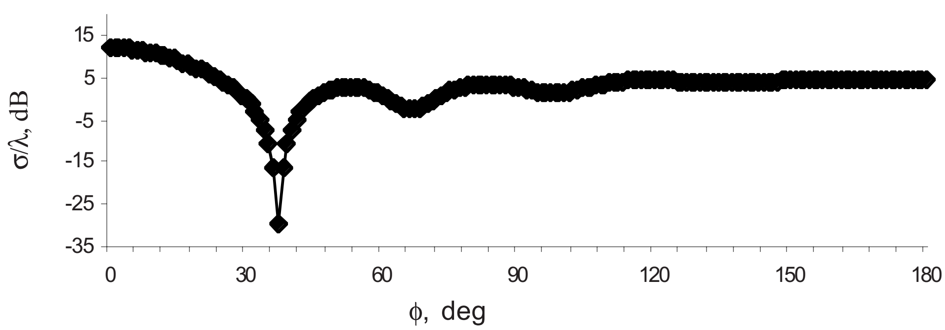

Figure 6: Conducting cylinder graph, H-polarized incidence wave

Test Case 2: Bistatic scattering width of a coated conducting cylinder A

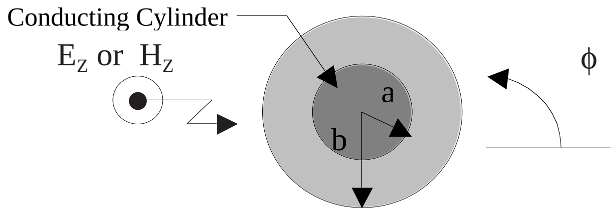

Figure 7: Coated Conducting Cylinder A

A coated conducting cylinder with inner radius of 1.0λ, outer radius of 1.5λ, angle of incidence 180°, and $\varepsilon_r = 2.0$ and $\mu_r = 1.0$ as shown in Figure 7 is considered. The bistatic scattering was computed in a constant θ-plane at θ = 30° for ϕ = 0° to 180° with E-polarized incidence wave and then an H-polarized incidence wave.

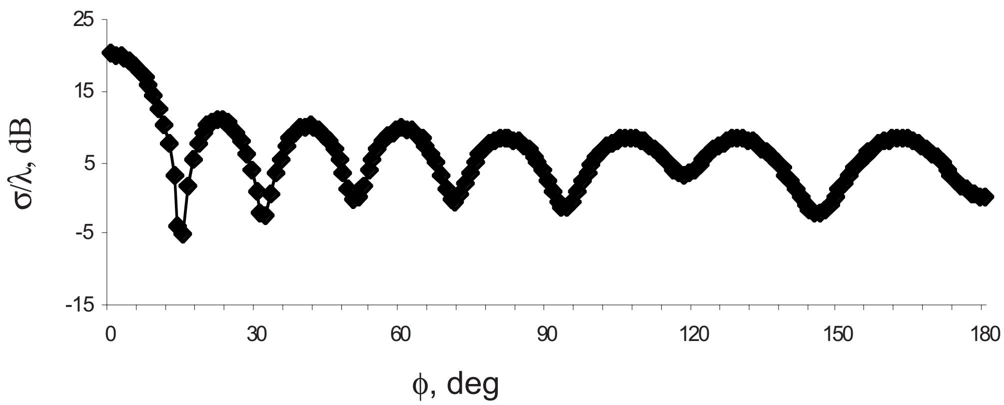

Figure 8: Coated conducting cylinder A graph, E-polarized incidence wave

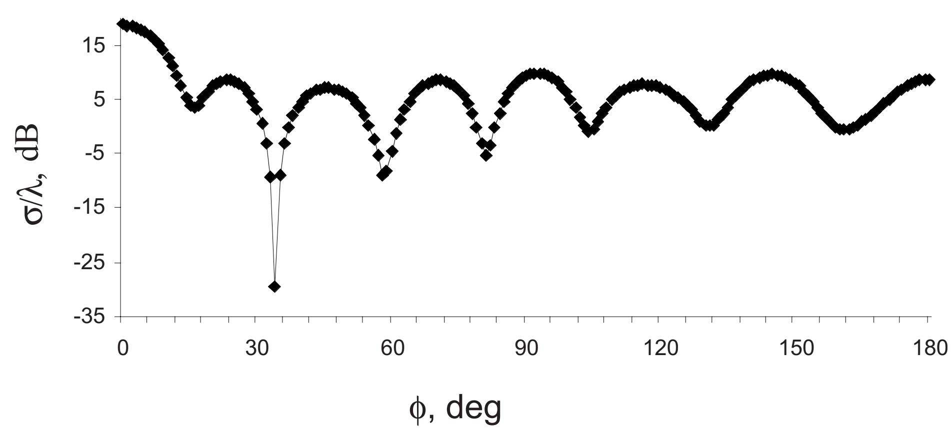

Figure 9: Coated conducting cylinder A graph, H-polarized incidence wave

Test Case 3: Monostatic scattering width of a conducting strip

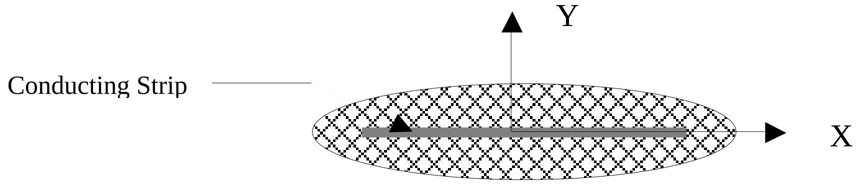

Figure 10: Conducting Strip

A conducting strip (infinite along z) of length 2.2λ, width of 0.04λ, and angle of incidence 180° with an artificial elliptical boundary with major axis 1.3λ and minor axis 0.3λ as shown in Figure 10 is considered. The monostatic scattering was computed in a constant θ-plane at θ = 30° for ϕ = 0° to 180° with E-polarized incidence wave and then an H-polarized incidence wave.

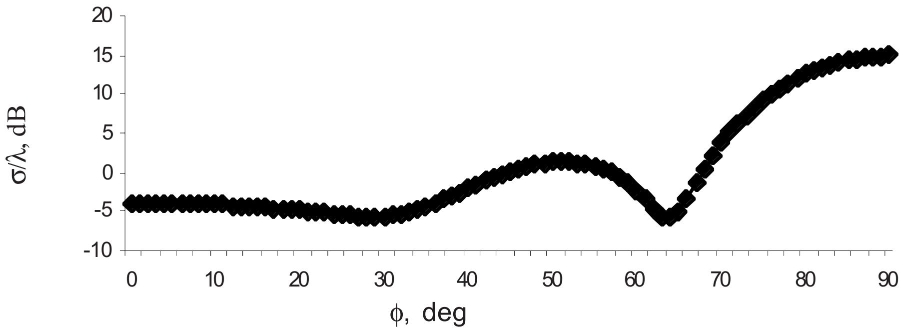

Figure 11: Conducting strip graph, E-polarized incidence wave

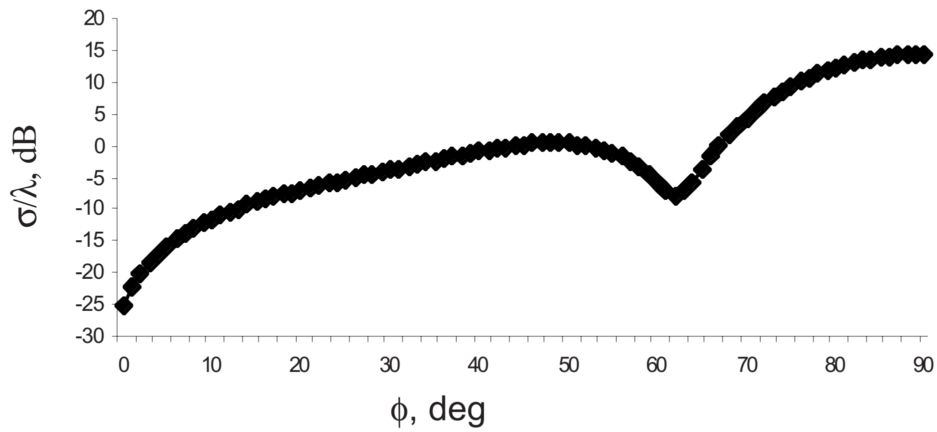

Figure 12: Conducting strip graph, H-polarized incidence wave

Test Case 4: Bistatic Scattering width of a coated conducting cylinder B

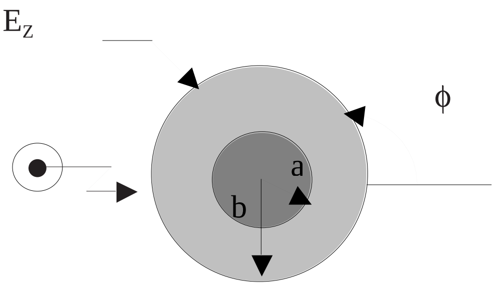

Figure 13: Coated Conducting Cylinder B

A coated conducting cylinder with inner radius of 1.0λ, outer radius of 1.5λ, angle of incidence 180°, and ε_r = 2.0 and μ_r = 2.0 as shown in Figure 13 is considered. The bistatic scattering was computed in a constant θ-plane at θ = 30° for φ = 0° to 180° with a H-polarized incidence wave.

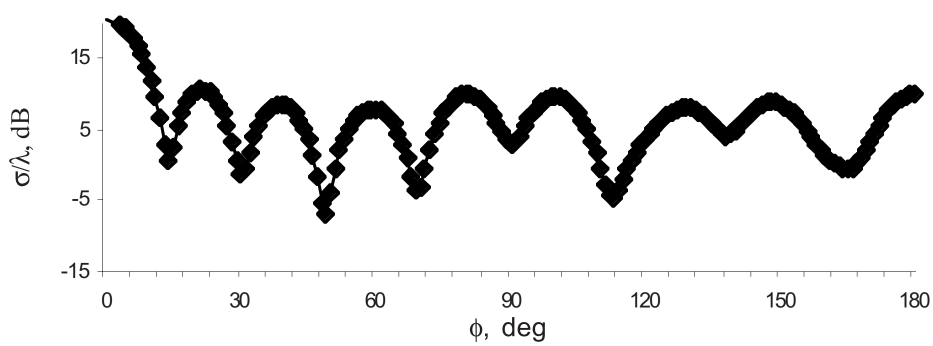

Figure 14: Coated conducting cylinder B graph, H-polarized incidence wave

Test Case 2: Bistatic Scattering width of an isosceles triangular metallic cylinder

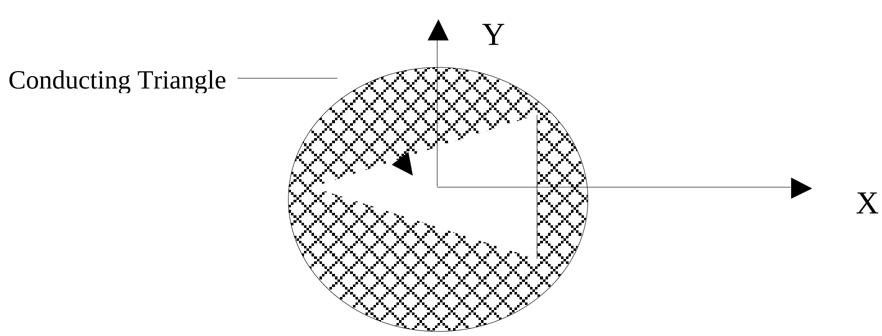

Figure 15: Isosceles metallic cylinder with artificial circular boundary

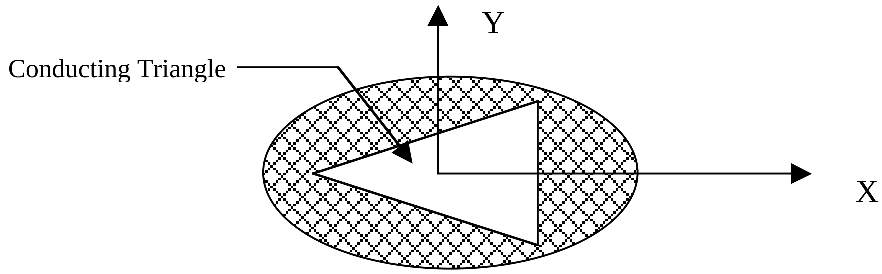

Figure 16: Isosceles metallic cylinder with artificial elliptical boundary

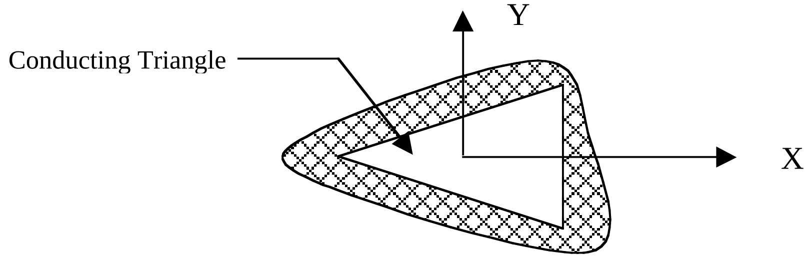

Figure 17: Isosceles metallic cylinder with artificial conformal boundary with blended corners

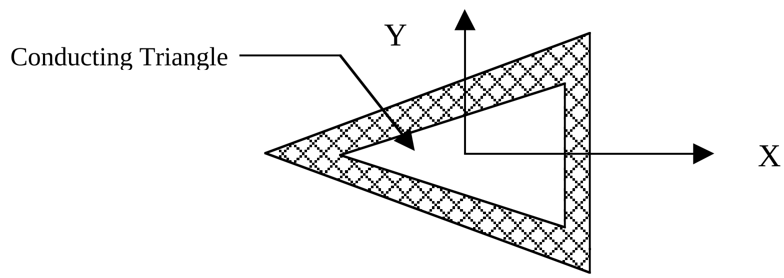

Figure 18: Isosceles metallic cylinder with artificial conformal boundary

To show the artificial boundary curve enclosing the cylindrical scattering structure may be of any shape, an isosceles triangular metallic cylinder is enclosed in a circle (Figure 15), an ellipse (Figure 16), a conformal boundary with blended corners (Figure 17), and a conformal boundary with sharp corners (Figure 18).

The isosceles triangular metallic cylinder has a base = $1.404\lambda_o$ and sides = $1.85\lambda_o$. The circular boundary has a radius $1.2\lambda_o$. The elliptical boundary has major axis $1.3\lambda_o$ and minor axis $1.1\lambda_o$. The conformal boundaries are approximately $0.2\lambda_o$ greater than the triangle. The bistatic scattering was computed in a constant θ-plane at $\theta = 30^o$ for $\phi = 0^o$ to 180^o with E-polarized incidence wave.

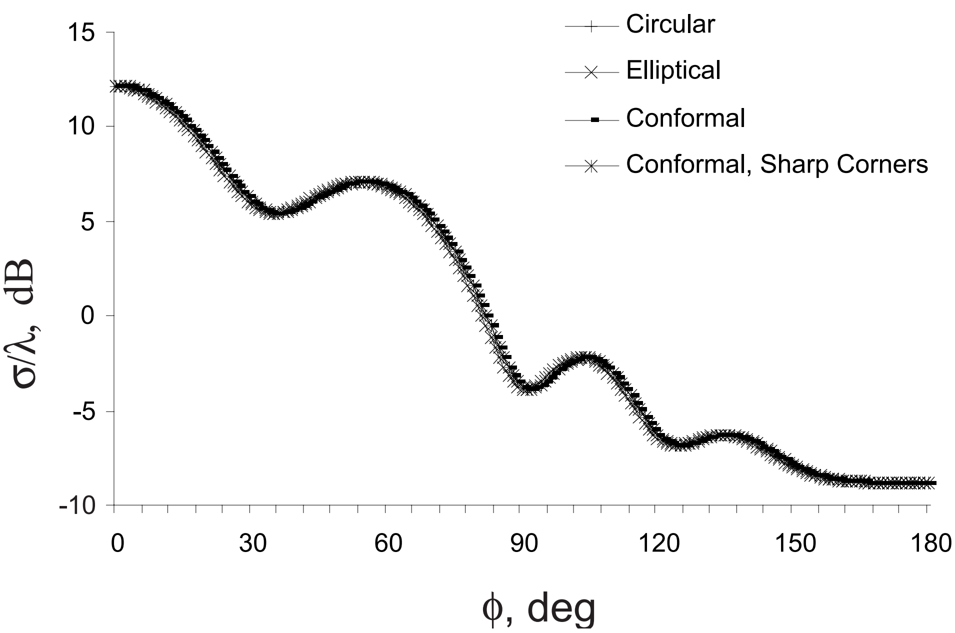

Figure 19: Isosceles metallic cylinder graph, E-polarized incidence wave

Test Case 5: Monostatic Scattering width of a microstrip transmission line

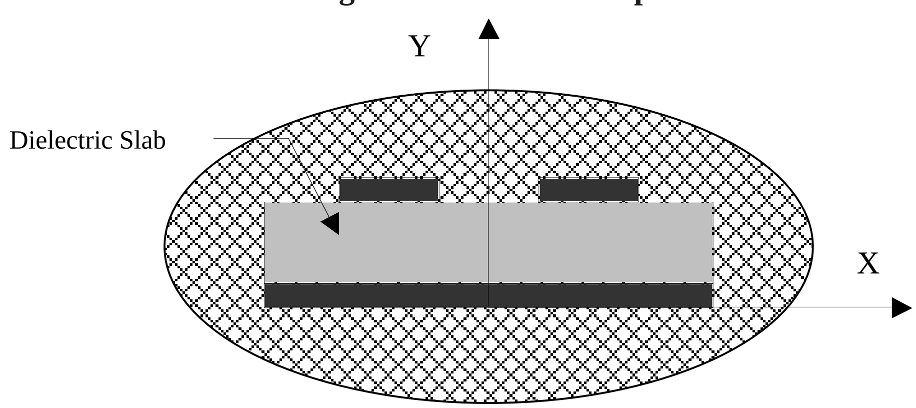

Figure 20: Microstrip transmission line

The microstrip transmission line in Figure 20 has an artificial elliptical boundary with major axis $0.6\lambda_o$ and minor axis $0.3\lambda_o$ and the following dimensions: length $w_1 = 0.9\lambda_o$, length $w_2 = 0.15\lambda_o$, height $t_1 = 0.02\lambda_o$, height $t_2 = 0.1\lambda_o$, and height $t_3 = 0.05\lambda_o$. The monostatic scattering was computed in a constant θ-plane at $\theta = 30^o$ for $\phi = 0^o$ to 90^o with E-polarized incidence.

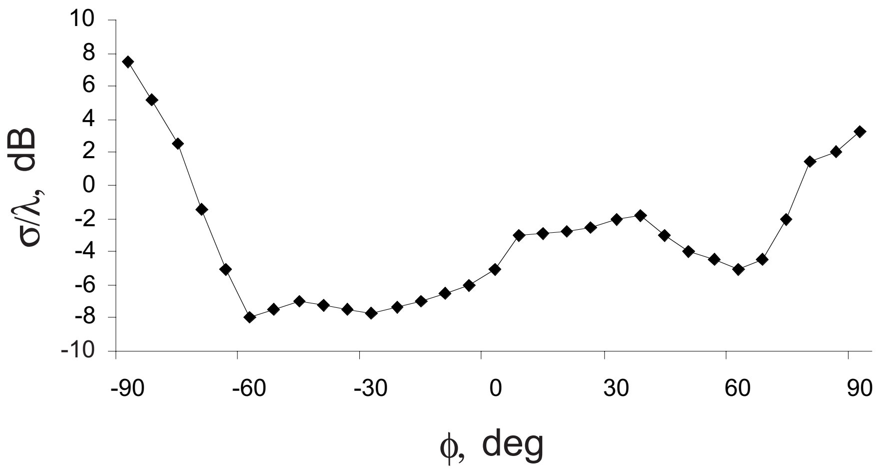

Figure 21: Microstrip transmission line graph, E-polarized incidence wave

Test Case 6: Monostatic Scattering width of a von Karman shaped conducting cylinder

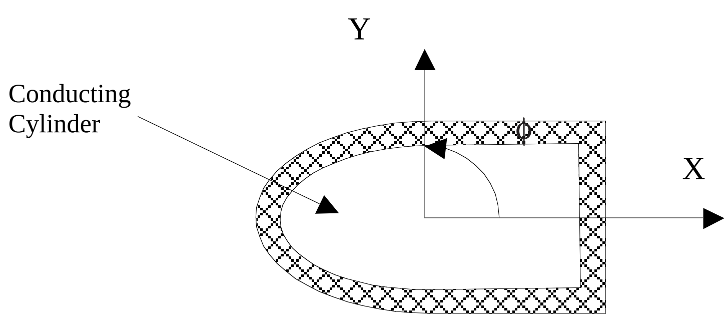

Figure 22: von Karman shaped conducting cylinder

The von Karman shaped conducting cylinder in Figure 22 has an artificial von Karman shaped boundary. The dimensions of the cylinder are height = $2.0\lambda_o$ and base = $1.0\lambda_o$. The dimensions of the artificial boundary are height = $2.2\lambda_o$ and base = $1.1\lambda_o$. The monostatic scattering was computed in a constant θ-plane at $\theta = 30^o$ for $\phi = 0^o$ to 180^o with E-polarized incidence.

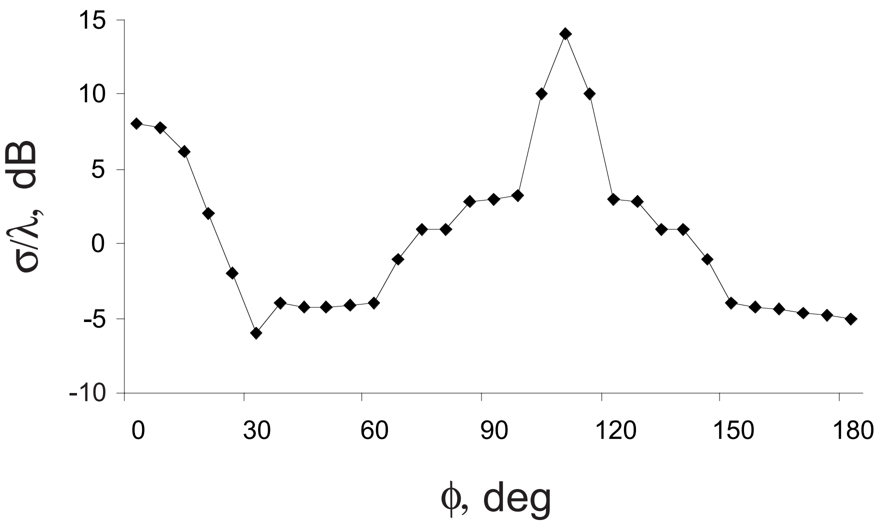

Figure 23: von Karman shaped conducting cylinder graph, E-polarized incidence wave

Test Case 7: Scattering pattern of circular dielectric cylindrical shell

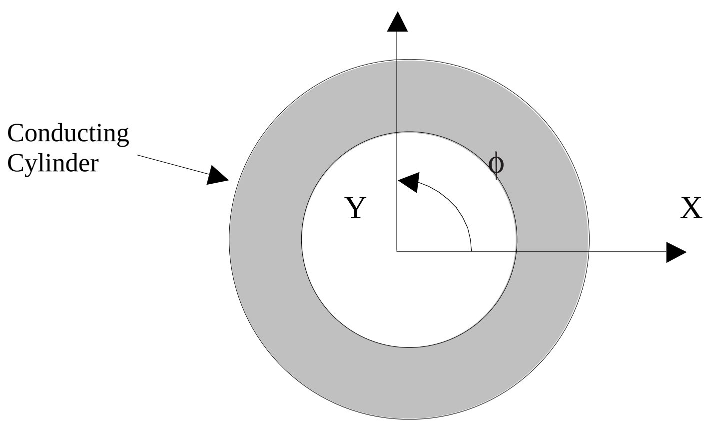

Figure 24: Circular dielectric cylindrical shell

A conducting cylinder with inner radius of 0.25λ, outer radius of 0.30λ, angle of incidence 180°, and $\varepsilon_r = 4.0$ and $\mu_r = 1.0$ as shown in Figure 24 is considered. The bistatic scattering was computed in a constant θ-plane at θ = 30° for φ = 0° to 180° with E-polarized incidence wave.

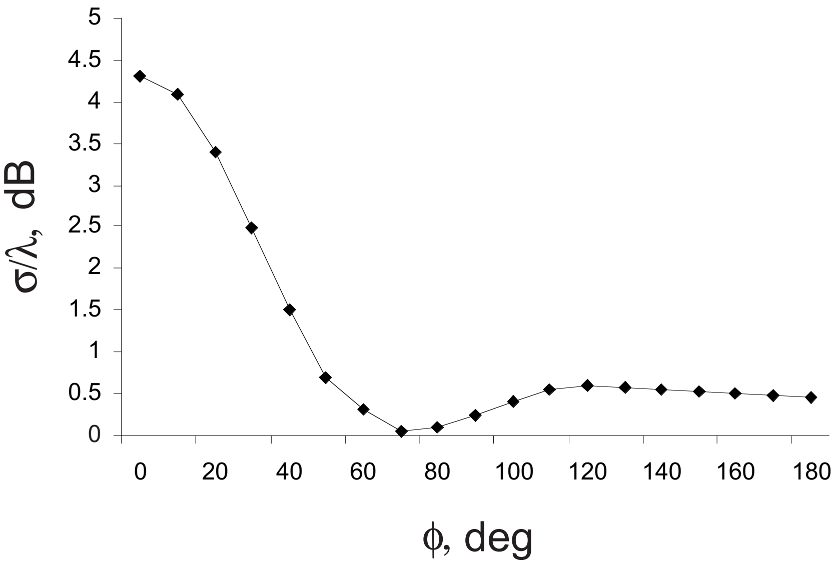

Figure 25: Circular dielectric cylindrical shell graph, E-polarized incidence wave

Test Case 8: Scattering pattern of a semicircular dielectric cylindrical shell

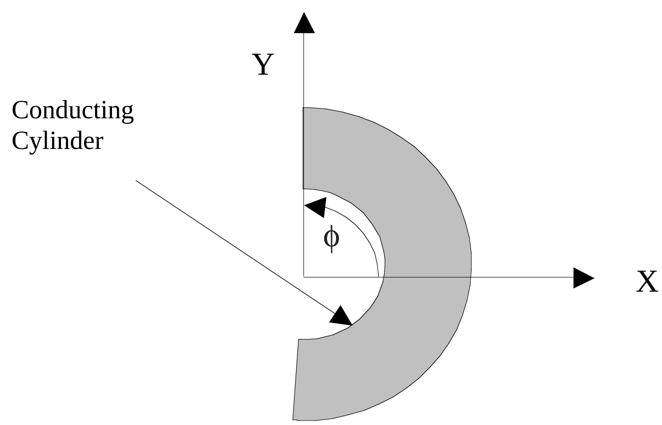

Figure 26: Semicircular dielectric cylindrical shell

A conducting semicircular cylindrical shell with inner radius of 0.25λ, outer radius of 0.30λ, angle of incidence 180^o, and $\varepsilon_r = 4.0$ and $\mu_r = 1.0$ as shown in Figure 24 is considered. The bistatic scattering was computed in a constant θ-plane at $\theta = 30^o$ for $\phi = 0^o$ to 180^o with E-polarized incidence wave.

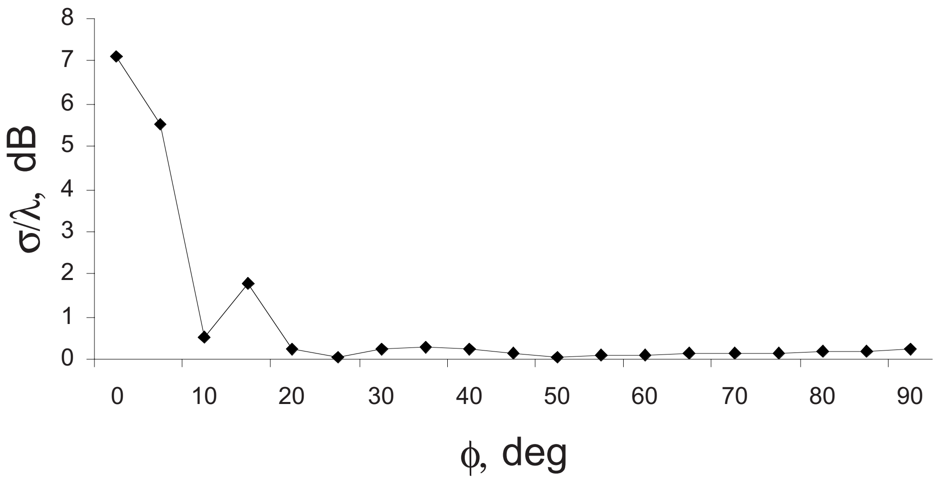

Figure 27: Semicircular dielectric cylindrical shell graph, E-polarized incidence wave

6.0 CONCLUDING REMARKS

The usage of the scattering code is demonstrated so that the user can get acquainted with the details of using the code with minimum possible effort. The flexibility of the code is demonstrated in a wide variety of test cases presented in Section 5. As no software can be bug free, the scattering code is expected to have hidden bugs that can only be detected by the repeated use of the code for a variety of geometries. Any comments or bug reports should be sent to the author. As the reported bugs are fixed and more features added to the code, future versions will be released. Information on future versions code can be obtained from:

Electromagnetics Research Branch (MS 490)
Airborne Systems Competency
NASA Langley Research Center
Hampton, VA 23681

7.0 REFERENCES

Deshpande, M.D., Cockrell, C.R., and C.J. Reddy: Electromagnetic Scattering Analysis of Arbitrarily Shaped Material Cylinder by FEM-BEM Method. NASA Technical Paper 3585. July 1996.

Richmond, Jack H.: Scattering by a Dielectric Cylinder of Arbitrary Cross Section Shape. IEEE Transactions on Antennas and Propagation. 1964.

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13. ABSTRACT *(Maximum 200 words)*
A user's manual for using FORTRAN code to perform electromagnetic scattering analysis of arbitrarily shaped material cylinders using a hybrid method that combines the finite element method (FEM) and the boundary element method (BEM) [1]. In this method, the material cylinder is enclosed by a fictitious boundary and the Maxwell's equations are solved by FEM inside the boundary and by BEM outside the boundary. The electromagnetic scattering on several arbitrarily shaped material cylinders using this FORTRAN code is computed to as examples.

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